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Ventilation Pre-heating Effectiveness of a PCM Solar Air Collector with Ventilated Window System

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Abstract

This paper proposed a PCM solar air collector with ventilated window system to store solar energy for ventilation pre-heating purpose. The PCM stores the solar energy when the solar radiation is available and releases the heat to the ventilated air when the room is occupied and the fresh air is needed. The additional heat gained from solar radiation is used as a substitute energy demand of the building. A conduction finite difference model is built in Energyplus to simulate the heat transfer of the PCM solar air collector and the energy balance of the system. The model is validated by a full-scale experimental test. The model is then used to evaluate the energy saving potential of applying the PCM solar air collector for residential and office buildings in 3 cities for the represent of 3 different climate zones. The climate analysis shows that the percentage of the days when PCM is activated is 33.11%, 33.77% and 62.91% for Copenhagen, Geneva, and Rome respectively in winter and spring seasons. The energy analysis found out that the HVAC energy saving potential of applying PCM solar air collector for residential building is 29.19%, 33.69% and 65.11% for Copenhagen, Geneva and Rome respectively. For office building it is 26.86%, 31.64% and 41.09% for Copenhagen, Geneva and Rome respectively.

Introduction

Building energy consumption for ventilation and HVAC systems is more than one-third of the total energy consumption for industry countries (Heiselberg et al., 2009), and is in growing trends because of the improvement of thermal comfort standards and climate changes. To diminish fuel consumption and carbon dioxide emission because of the building energy consumption, it is necessary to implement some innovate technologies and solutions for the building environment. Phase change material (PCM) works as thermal energy storage (TES) is a good solution to increase the thermal mass of the building system because of its high latent heat storage capacity (Pomianowski, Heiselberg, & Jensen, 2013). This intense heat storage ability makes it smaller in volume in comparison with other building thermal mass materials. Another advantage of PCM is that the phase change occurs in an almost constant temperature, which makes it less possible for the temperature stratification in the space (Pomianowski, Heiselberg, & Zhang, 2013). With the proper choice of PCM, the phase change occurs around room temperature, which is good for the thermal comfort in the indoor environment.

Applying PCM into ventilation systems has the advantage of increasing the surface heat transfer coefficient of the material. As a consequence, the charging and discharging efficiency of PCM are improved. Several researchers have successfully developed night ventilation systems with PCM. Alvaro studied a PCM ventilated façade numerically (De Gracia, Navarro, Castell, & Cabeza, 2013) and experimentally (De Gracia, Navarro, Castell, Ruiz-Pardo, et al., 2013) about its thermal performance and energy saving potential, and developed the control strategies of this system based on reinforcement learning (Alvaro De Gracia, Fernández, Castell, Mateu, & Cabeza, 2015). Those works indicate that applying PCM into ventilation façade has a good potential to improve night cooling effect and building energy efficiency. The authors also emphasized the importance of control strategy optimization during those studies. Other researches include the implement of PCM in packed bed storage (Takeda, Nagano, Mochida, Shimakura, & Shimakura, 2004; Yanbing, Yi, & Yinping, 2003), ceiling board (Kondo & Iwamoto, 2006), HVAC system (Yamaha & Misaki, 2006), heat pipe (Awbi, Turnpenny, Etheridge, & Reay, 2000) and slurry tank (Wang & Niu, 2009). Most of the implements lead to the improvement of thermal comfort level or building energy conservation.

As the increasing trend of applying PCM into building systems, many building simulation software have developed modules for PCM inputs. Researchers have successfully modeled PCM in those simulation software with experimental validation, including Fluent (Susman, Dehouche, Cheechern, & Craig, 2011), COMSOL Multiphysics (Y. Hu & Heiselberg, 2018; Virgone & Trabelsi, 2016), Trnsys (Ahmad, Bontemps, Sallée, & Quenard, 2006; Dentel & Stephan, 2013), EnergyPlus (Evola, Marletta, & Sicurella, 2014; Ramakrishnan, Wang, Alam, Sanjayan, & Wilson, 2016; Saffari, de Gracia, Ushak, & Cabeza, 2016; Tabares-Velasco & Griffith, 2012). EnergyPlus is a wildly used building energy simulation software. It simulates the heat transfer process of the building with different building equipment. There are several thermal comfort models available to make an assessment of the thermal comfort of the indoor environment. The conduction finite-difference (CondFD) method is used to simulate the PCM instead of the conduction transfer function (CTF) method for building

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constructions, because that the heat capacity and thermal conductivity and some other parameters of PCM are changing along with temperature (Kośny, 2015). The fully implicit numerical model with the enthalpy method was developed by Pedersen (2007). The enthalpy of the PCM as a function of temperature is used to calculate the equivalent specific heat of the PCM at each time step. The hysteresis of PCM is defined by the difference of melting/freezing ranges and peak temperatures.

This paper aims to evaluate the building energy saving potential of the ventilated window with PCM solar air collector system in EnergyPlus model for residential and office buildings in 3 cities in different climate zones. The details of the EnergyPlus model is first presented and validated by experimental data. Then the climate characteristics of the 3 cities are analyzed. Furthermore, the control strategy of the system is developed and the temperature profiles of the model with PCM solar air collector in relation to the solar radiation and outdoor air temperature are investigated. Next, energy demands of models with PCM solar air collector and without PCM solar air collector are compared and the energy saving potentials of applying PCM solar air collector are calculated for residential and office buildings in the 3 cities.

Methods

This work builds the model of the PCM solar air collector and ventilated window system in the building energy simulation software EnergyPlus. It uses conduction finite difference (CondFD) algorithm to complement the original conduction transfer function (CTF) algorithm in cases when the PCM or changeable thermal conductivity is simulated. The advantage of this algorithm is that it can simulate short time steps such as 1 minute (*EnergyPlus Documentation Engineering Reference*, 1996).

The finite difference model uses fully implicit or semi-implicit scheme coupled with an enthalpy-temperature function for the energy calculation of Phase Change Material. The fully implicit scheme is also called Crank-Nicholson scheme. The implicit formulation is shown in Equation (1).

$$C_p\rho\Delta x\frac{T_i^{j+1}-T_i^j}{\Delta t}=\frac{1}{2}\left[\begin{array}{l}\left(k_W\dfrac{\left(T_{i+1}^{j+1}-T_i^{j+1}\right)}{\Delta x}+k_E\dfrac{\left(T_{i-1}^{j+1}-T_i^{j+1}\right)}{\Delta x}\right)\\+\left(k_W\dfrac{\left(T_{i+1}^{j}-T_i^{j}\right)}{\Delta x}+k_E\dfrac{\left(T_{i-1}^{j}-T_i^{j}\right)}{\Delta x}\right)\end{array}\right] \quad (1)$$

Where

C_p is the specific heat of the material;

ρ is the density of the material;

Δx is the finite difference layer thickness;

Δt is the calculation time step;

T is the temperature of the node;

i is the node been modeled;

i+1 is the adjacent node to interior of construction;

i-1 is the adjacent node to exterior of construction;

j+1 is the new time step;

j is the previous time step;

k_W is the thermal conductivity for interface between i node and i+1 node;

k_E is the thermal conductivity for interface between i node and i-1 node.

$$k_W=\frac{\left(k_{i+1}^{j+1}-k_i^{j+1}\right)}{2} \quad (2)$$

$$k_E=\frac{\left(k_{i-1}^{j+1}-k_i^{j+1}\right)}{2} \quad (3)$$

The heat capacity of the material is calculated from the user input enthalpy function, as shown in Equation (4). If the hysteresis of the PCM is considered, the heat capacity of the current moment not only depends on the previous temperature but also previous phase change state, as shown in Equation (5).

$$C_p=\frac{h(T_i^{j+1})-h(T_i^j)}{T_i^{j+1}-T_i^j} \quad (4)$$

$$C_p=f(T_{i,j},T_{i,j-1},PhaseState_j,PhaseState_{j-1}) \quad (5)$$

A room (3.6 m×3.6 m×3.5 m) on the first floor of a 3 floors building is modeled with ideal loads air system to calculate the energy load to maintain the room temperature at 22-26 °C. Two types of rooms are simulated: the residential and the office. The apartment is occupied during 16:00-06:00. The office room is occupant during 8:00-17:00. The lights, other equipment and ventilation schedule are all the same as the occupant schedule. The heat rate of the light and other equipment for the office room is 30 W/m^2 during the occupant hours. For the residential room, the maximum heat rate is 158 W and the heat peak is 17-22 h (Wittchen & Kim Bjarne, 2004). The EneryPlus model includes 3 thermal zones: the room zone, the double window zone, and the PCM solar air collector zone. The ventilated window is facing south. The ventilation air distribution starts from the bottom of the solar air collector zone, goes through the solar air collector and double window zones into the indoor room. The room has only one external wall on the south façade with a U value of 0.136. The other walls and ceiling are modeled as internal constructions with adiabatic boundary condition. The infiltration level of the room is set as 0.5 air change per hour. Figure 1 shows the air distribution and details of the PCM solar air collector and ventilated window. The model compares the energy load of the systems with PCM solar air collector and without PCM solar air collector. The former system is ventilated through the PCM solar air collector during the occupied hours, while the latter is ventilated directly from the outdoor during the same period. The air flow rate for both ventilation systems is 30 m^3/h.

The PCM solar air collector is modeled as a separate thermal zone from the double window and the room. It is made by 0.010 m PCM plates and 0.005 m air gaps with wooden frame and glass cover. The heat capacity of the PCM is set according to DSC measurement (Hu &

Heiselberg, 2018). The total volume of the PCM in the solar air collector is 0.06 m^3 and the total latent energy storage potential is 6.04 MJ.

The double glazing window cavity is in the same width as the PCM solar air collector. The double glazing window is made by two layers of 0.006 m glass and a 0.01 m air cavity between them. The U value and g value of the glasses are seen in Figure 5(a). The reference model has the same configurations except that the PCM in the solar air collector part is removed.

The model result of the PCM temperature during 550 W heating for 6 hours is compared with a full-scale experimental test. The details of the experimental process can be found in (Hu, Heiselberg, Johra, & Guo, 2019). The PCM temperature curve from the result of the EnergyPlus model has a clearer phase transition period than from the experiment, see Figure 2. It is because the curve from experimental test takes the average temperature of 12 measurement points in the different heights of the PCM plates, while the EnergyPlus model takes one-dimensional heat transfer for PCM heat transfer calculation. However, the errors of the model results at each measurement time are all under 20%, which is calculated based on Equation (5). The average error is 8.27%.

$$\varepsilon = \frac{|\text{experimental data- calculated data}|}{\text{experimental data}} \qquad (5)$$

Results and discussions

The climate condition is first analyzed to see the potential of the applicant of the PCM solar air collector, including the daily mean air temperature and the daily mean received solar radiation by the south surface of the PCM solar air collector. Figure 3 shows the daily average of outdoor air dry bulb temperature in 3 different cities for winter and transition seasons to represent 3 different climates: cold (Copenhagen), mild (Geneva) and hot (Rome) climate. It is seen that for most of the time Rome has the highest daily mean outdoor air temperature, then is Geneva and Copenhagen. For some days of April in Rome, the daily mean air temperature is quite high, which indicates the cooling supply may be needed for the air conditioning system.

Figure 4. Shows the daily solar radiation received by the south surface of the solar air collector in 3 different cities. For Copenhagen, the daily received solar radiation during the winter season is not so high. But it is higher in spring (from March to April). The average received solar radiation on south surface is 1.92 KWh/day/m^2, 2.03 KWh/day/m^2, and 2.93 KWh/day/m^2 for Copenhagen, Geneva and Rome respectively.

Figure 5 shows the operation control strategy of the ventilated window with PCM solar air collector. The outdoor air goes from the bottom of the heat exchanger, through the double window and is supplied to the indoor room when the indoor air temperature is lower than 24 °C. It is heated up by the PCM solar air collector. The heat of the PCM solar air collector comes from the solar radiation during the sunny daytime. When the indoor air temperature is higher than 24 °C, the room ventilation is directly from outdoor through bypass mode, to prevent the room from overheating. At the meantime, the double window part is ventilated by self-cooling ventilation, to decrease the indoor heat gain through the window. The ventilated window without PCM solar air collector system has the same control strategy, except that there is no PCM solar air collector available.

Figure 6 shows the temperature profiles of the model with PCM solar air collector for residential building in Copenhagen. The air temperature in the double glazing window has a smaller time lag than the PCM temperature with regards to the solar radiation, due to its heat transfer to both indoor and outdoor environment, while the PCM solar air collector only transfers heat to the outdoor environment because of the inner insulation. Take 13th April for example, the air temperature in the double window is lower than the PCM temperature after 13:00 because the former keeps decreasing afterwards. At 18:00, the ventilation fan for the PCM solar air collector is turned on. The air temperature in the double window increased 9.66 K immediately due to the heat supply from the PCM solar air collector. Then it drops as the PCM temperature is decreasing. The PCM is considered fully active when its temperature reaches 24 °C, which is around 11:00. The total average solar energy needed to activate the PCM is 2.08 KWh/m^2, which are 33.11%, 33.77% and 62.91% of the days represented in Figure 4 for Copenhagen, Geneva, and Rome respectively.

Figure 7 shows the monthly energy demand for the models with and without PCM solar air collector for residential and office building in 3 cities. The fan energy is 1.21% of the total HVAC energy demand for the system with PCM, and similar as the fan energy consumption without PCM solar air collector, which is ignored in the result analysis about energy saving potential. The overall heating and cooling energy demand for the model with PCM solar air collector is lower than it without PCM solar air collector. Residential building has a higher heating energy demand and a lower cooling energy demand than office building in general. For all the cities, the models in Copenhagen has the highest heating energy demand, while the models in Rome has the highest cooling energy demand.

Table 1 shows the energy demand for the models with and without PCM solar air collector and the energy saving potential of using the PCM solar air collector for residential and office buildings in the 3 cities. Among them, the models in Copenhagen have the highest energy saving amount. However, the energy saving percentage is the lowest, due to the high energy demand. The models in Rome have the lowest energy saving amount but the highest energy saving percentage. For the same city, residential buildings have higher energy saving amount as well as energy saving percentage than office buildings. The reason is that the office buildings have higher internal gains than the residential buildings, which results in a higher energy demand.

Conclusions

This paper proposed a PCM solar air collector with a ventilated window system to make the most use of solar energy for ventilation pre-heating purpose. The PCM solar air collector stores solar energy during the daytime and releases the heat to the ventilated air when the ventilation pre-heating is needed. The bypass and double window self-cooling mode is added to the control strategy to prevent the overheating of the room. A conduction finite difference Energyplus model is built to evaluate the heat transfer process and the energy saving potential of the PCM solar air collector compare to the same system without PCM solar air collector. The model is validated by a full-scale experimental test.

The results of climate analysis show the temperature trends and solar energy availability of the 3 different cities in winter and spring. The daily mean temperature of Rome is the highest, then is Geneva. The similar trend is found out for the average received solar radiation by south surface. The analysis of temperature profiles of the model with PCM solar air collector in relation with solar radiation has the conclusion that the percentage of the days when PCM is activated is 33.11%, 33.77% and 62.91% for Copenhagen, Geneva, and Rome respectively.

The conclusions for building energy demand analysis are that models in Copenhagen have the most energy saving amounts. The models in Rome has the highest energy saving percentage. With PCM solar air collector, the residential building saves more energy than office building. The energy saving potential for residential building is 29.19%, 33.69% and 65.11% for Copenhagen, Geneva and Rome respectively. While the energy saving potential for office building is 26.86%, 31.64% and 41.09% for Copenhagen, Geneva and Rome respectively.

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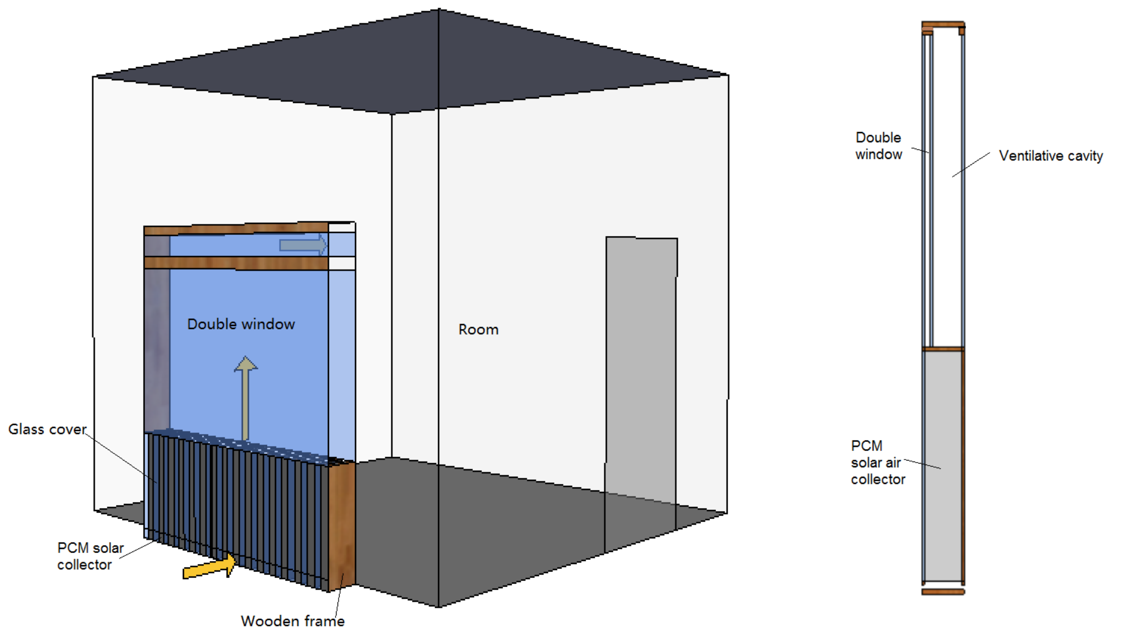

(a) The installation of the system.

(b) The details of the PCM solar air collector and vwntilative window.

Figure 1: Sketch and the air distribution of the ventilated window with PCM solar air collector system.

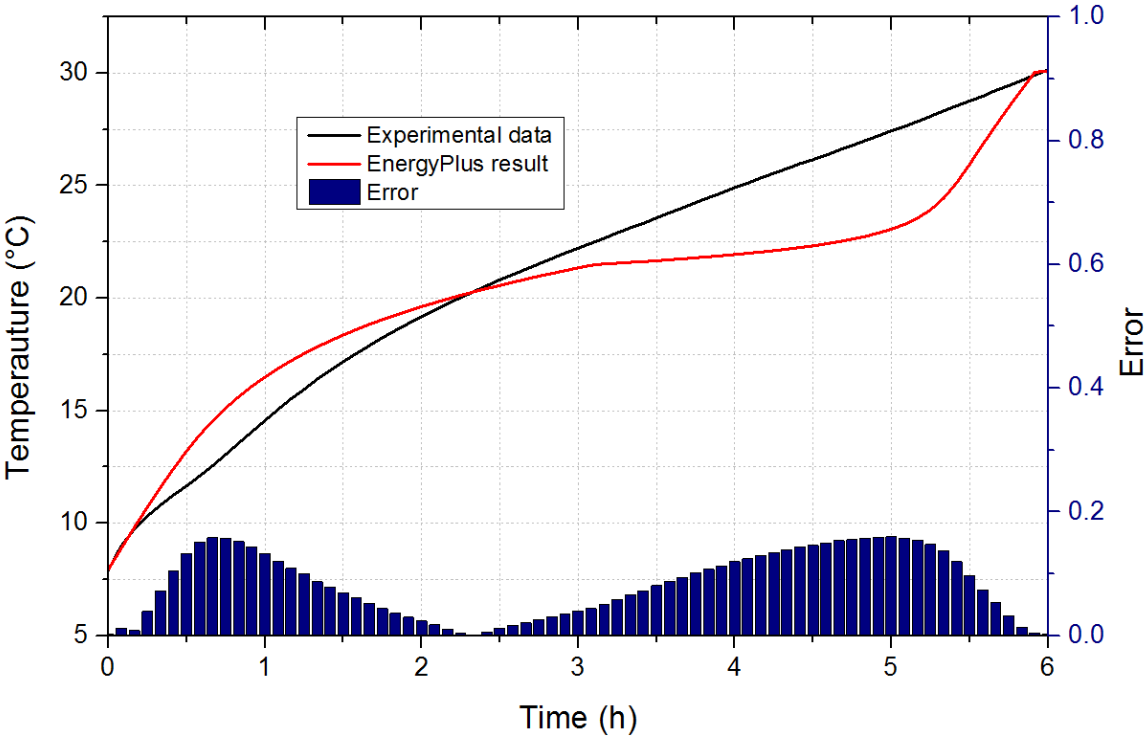

Figure 2: Comparison of the PCM temperature between the experimental data and the model result.

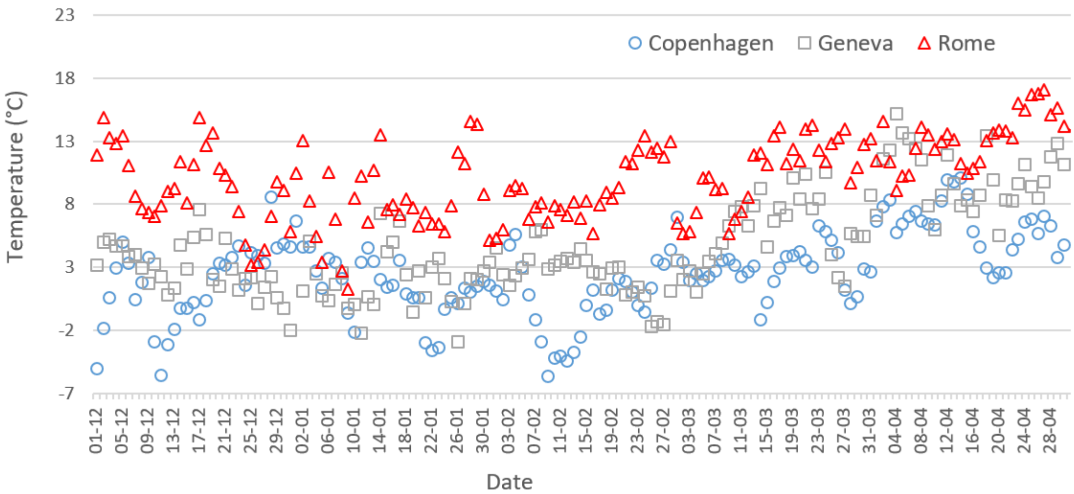

Figure 3: The daily average of outdoor air dry bulb temperature in 3 different cities for winter and transition seasons.

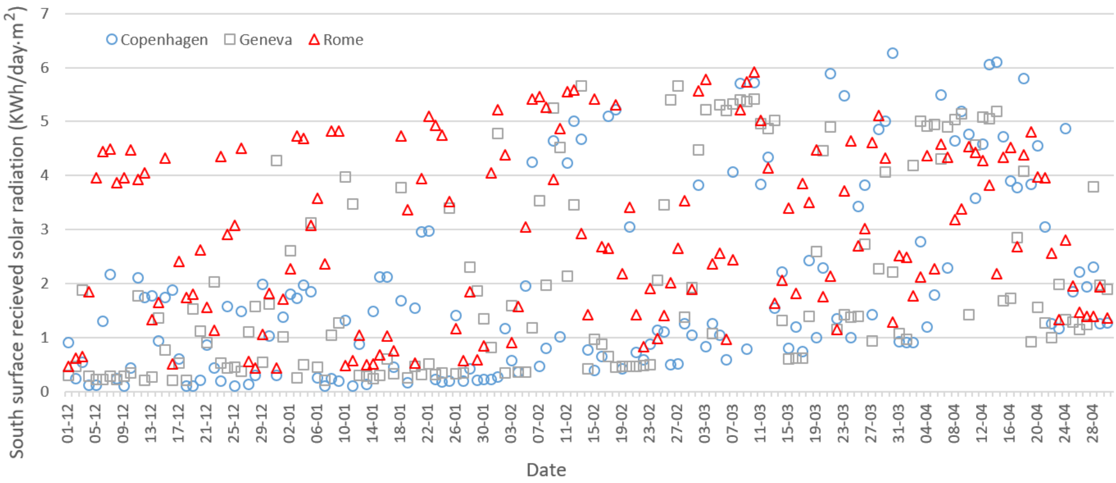

Figure 4: The daily received solar radiation of the window surface in 3 different cities for winter and transition seasons.

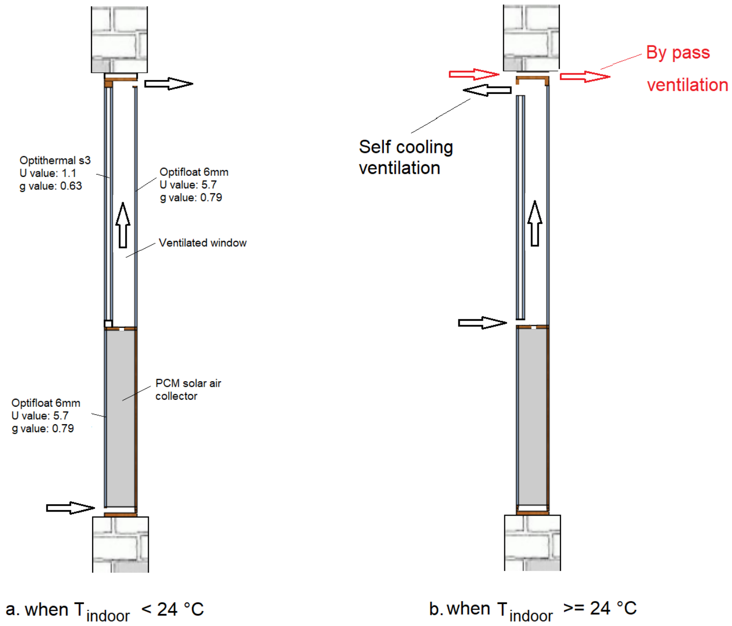

Figure 5: The operation control strategy.

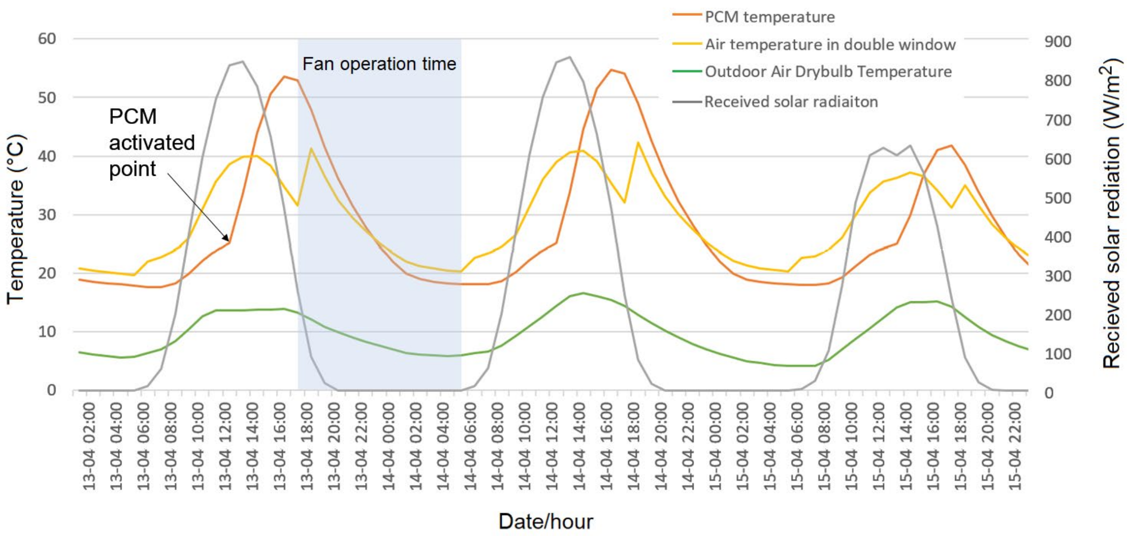

Figure 6: Temperature profiles of the model with PCM solar air collector for residential building in Copenhagen.

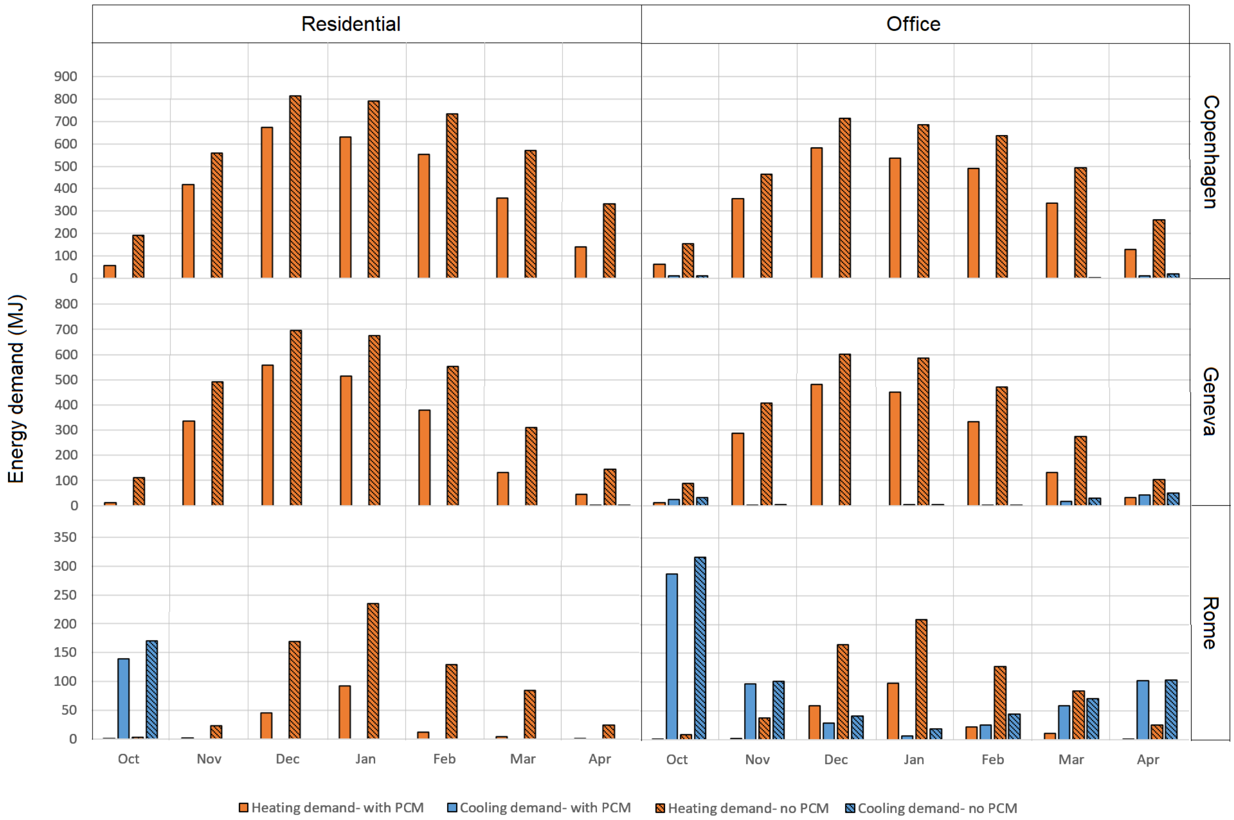

Figure 7: The energy demand for the models with and without PCM solar air collector.

Table 1: The total energy demand for the models with and without PCM solar air collector and the energy saving potential of using PCM solar air collector.

City	Residential energy demand (MJ)			Energy saving percentage	Office energy demand (MJ)			Energy saving percentage
	With PCM	Without PCM	Energy saving amount		With PCM	Without PCM	Energy saving amount	
Copenhagen	2829.02	3994.98	1165.96	29.19%	2512	3434.52	922.52	26.86%
Geneva	1978.14	2983.29	1005.15	33.69%	1815.39	2655.63	840.24	31.64%
Rome	292.75	838.99	546.24	65.11%	796.82	1352.63	555.81	41.09%